Scotland's Rural College

Legume-based green manure crops

Baddeley, John A; Pappa, Valentini A; Pristeri, Aurelio; Bergkvist, Göran; Monti, Michele; Reckling, Moritz; Schläfke, Nicole; Watson, Christine A

Published in:
Legumes in Cropping Systems

DOI:
10.1079/9781780644981.0125

Print publication: 01/01/2017

Document Version
Publisher's PDF, also known as Version of record

8 Legume-based Green Manure Crops

John A. Baddeley,[1]* Valentini A. Pappa,[2] Aurelio Pristeri,[3] Göran Bergkvist,[4] Michele Monti,[3] Moritz Reckling,[5] Nicole Schläfke[5] and Christine A. Watson[1]

[1]*Scotland's Rural College, Edinburgh, UK;* [2]*Texas A&M University, Texas, USA;* [3]*Department of Agraria, Mediterranean University of Reggio Calabria, Reggio Calabria, Italy;* [4]*Swedish University of Agricultural Sciences, Uppsala, Sweden;* [5]*Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany*

Abstract

Legume-based green manures (LGMs) are crops that are grown with the specific purpose of improving soil quality and consequently the long-term productivity of crops. Although the traditional focus has been on the supply of nitrogen (N) to the system, they have a wide range of potential benefits that include improving soil quality, reducing soil erosion and increasing the biodiversity of farmland. LGMs are a key component of organic farming systems where the use of synthetic N fertilizers is not permitted. However, increases in the cost of inputs, concerns about environmental impacts of intensive use of agrochemicals, and the recently announced measures for the 'greening' of the European Common Agricultural Policy have led to renewed interest in the use of LGMs more widely. In Europe, the legumes in LGMs may be annual or perennial plants, grown on their own or more often as part of crop mixtures with a range of other crop types such as grasses or brassicas. The legumes most commonly grown are the clovers (*Trifolium* spp.), particularly red and white clover. Other legumes that may be grown to suit particular local goals or constraints include *Medicago* spp. (lucerne (alfalfa) and black medic), trefoils (*Lotus* spp.), vetches (*Vicia* spp.), lupins (*Lupinus* spp.), other minor forage legumes and grain legumes. To maximize fertility building in organic farming systems, LGMs are grown in place of cash crops for some of the crop rotation. In more intensive systems, LGMs may be grown for short periods between phases of regular crop production. This chapter reviews the use of LGMs in Europe and considers factors that affect N fixation in them and the transfer of fixed N to following crops. It examines how they can be integrated into practical rotational cropping systems and whether the economics of this makes the use of LGMs profitable. However, LGMs will not be agronomically or economically viable in all systems, and in these cases other types of green manures may be more appropriate. As demand for multifunctional agricultural systems grows, and is increasingly required by European agricultural policies, so does the potential for greater use of LGMs.

*john.baddeley@sruc.ac.uk

Introduction

A green manure may be broadly defined as any crop that is grown with the specific purpose of improving the soil, and by implication the crops that are subsequently grown in it. They have a wide range of potential benefits that include reducing the loss of nutrients to the environment through leaching and surface runoff, improving soil structure and quality, reducing soil erosion, and increasing the biodiversity of farmland. Green manures improve soil quality by increasing organic matter content, enhancing structure and promoting more diverse and biologically active microbial communities, and they potentially reduce the use of plant protection products and fertilizers. They are annual or perennial plants, grown on their own or more often in crop mixtures, for a few months or up to several years between periods of regular crop production. In long-term orchard and vineyards they are grown between trees and vines.

Legume-based green manures (LGMs) are grown with the specific aim of increasing nitrogen (N) availability in a system by making use of the N fixed from the atmosphere by the legume. Overall, this process is the product of two processes: (i) N fixation while the LGM is growing; and (ii) transfer of any accumulated N to following crops once the LGM has been incorporated (ploughed in).

The use of green manures has a long history in agriculture. Reports relating to the 5th century BC refer to their benefits being as 'good as silk-worm excrement' for the soil in China. The ancient Greeks are recorded as incorporating faba beans (*Vicia faba* L.) into soil around 300 BC and Roman farmers were advised to sow their crops 'where grew the bean, the slender vetch, or the fragile stalks of the bitter lupine' (Pieters, 1927). The use of LGMs declined after World War II due to the increased use of fertilizers and herbicides. They continue to be a key component of organic farming systems, where the use of synthetic N fertilizers is not permitted. However, recent increases in the cost of inputs, concerns about environmental impacts of intensive use of agrochemicals, and the recently announced measures for the 'greening' of the European Common Agricultural Policy, have led to renewed interest in the use of LGMs more widely (Stobart and Morris, 2011).

This chapter reviews the use of LGMs in Europe and considers factors that affect N fixation in them and the transfer of fixed N to following crops. It examines how they can be integrated into practical rotational cropping systems and whether the economics of this makes the use of LGMs profitable.

Types of LGMs

Given that the primary aim is usually to fix atmospheric N, most LGMs are grown over the summer period when conditions for plant growth and N fixation are at their best. In all but the hottest areas of Europe this is over summer. Farmers have a wide choice of species to grow, coupled with flexible management options. The advantages of using a summer-grown LGM must be weighed against the disadvantage that they often replace a more profitable crop in the rotation.

In contrast, overwintering LGMs are either undersown into the main crop or sown in autumn, and incorporated into the soil the following spring, thus not taking the place of a cash crop. This is preferable to leaving the ground with no cover during the winter, but N fixation is often limited by the poor growing conditions at this time of year. In addition, the choice of species is restricted and weather windows for sowing and incorporation are usually narrow. Longer-term LGMs are usually established for 2 or 3 years as a part of an arable rotation (leys). On farms with livestock, the leys are usually grazed or cut for silage, whereas in a stockless farm they are normally cut monthly during the summer months. The leys can be legume-only or more frequently a mixture of legumes and other species, most commonly grasses.

Legume Species Suitable for Green Manures

In most situations, the main factors influencing crop choice are: (i) agronomic performance in terms of establishment and productivity; (ii) compatibility with the existing rotation; and (iii) the composition of the residue which determines the breakdown characteristics of the LGM. However, information on the ability of different species to suppress weeds and timing of flowering may also be important considerations. At a higher level, the issue of whether the sward is cut or grazed also needs to be taken into account, as some species may not tolerate mowing or be compatible with certain livestock. While the majority of species grown in LGMs are forage legumes, some grain legumes are also used. Below is a brief summary of the main legume species grown in LGMs in Europe. Further detailed information may be found in other chapters of this book or is readily available elsewhere, and examples of some common LGMs are shown in Fig. 8.1.

Clovers

Trifolium spp. (clovers) are the legumes most widely used in LGMs. There are many species with different characteristics that can be used in a wide variety of LGMs. They are small annual, biennial or short-lived perennial herbaceous plants with characteristic trifoliate leaves.

Trifolium repens L. (white clover) is commonly used for grazing leys or intercropping. It is very persistent and grows close to the ground. There are many cultivars available and these are characterized by the size of the leaves: small- (e.g. 'Aberystwyth'), medium- (e.g. 'AberDai') and large- (e.g. 'Alice') leaved.

Trifolium pratense L. (red clover) is higher-yielding, less persistent and more drought-tolerant than white clover. It does not grow well at a pH below 5.5. The cultivars are separated into two groups: (i) early types (e.g. 'Merviot') that grow in early spring and most of the yield is from the first cut; and (ii) late types (e.g. 'Britta') that can be used in medium-term leys.

Trifolium incarnatum L. (crimson clover) is a frost-sensitive annual with brightly coloured flowers. Although it does not recover well after cutting, it may

Fig. 8.1. Legume species suitable for green manures. (A) White clover, (B) red clover, (C) lucerne, (D) crimson clover, (E) birdsfoot trefoil and (F) winter vetch. (Photo credits: John Baddeley.)

be used for forage when young. It grows and flowers rapidly from seed so can be used as an early food source for pollinators or as a weed suppressor.

There are several other less widely used clover species that can be useful for LGMs under specific climatic and soil conditions. These include: Alsike clover (*Trifolium hybridum* L.), subterranean clover (*Trifolium subterraneum* L.), strawberry clover (*Trifolium fragiferum* L.), yellow suckling clover (*Trifolium dubium* Sibth.), rose clover (*Trifolium hirtum* All.), Caucasian clover (*Trifolium ambiguum* M. Beeb.) and berseem or Egyptian clover (*Trifolium alexandrinium* L.).

Medics

Medicago is a genus with many similarities to clovers, and two species are widely used in LGMs.

Medicago sativa L. (lucerne or alfalfa) is a large perennial plant with a deep taproot and best known as a forage crop. It prefers a soil pH over 6 in relatively warm and dry climates but can be used in colder areas provided they are not too wet, and can produce the highest annual yield of all forage legumes (up to 15 t/ha). Inoculation of seeds with appropriate rhizobia is usually necessary.

Medicago lupulina L. (black medic) is an annual or short-lived perennial suitable for summer LGMs. It is almost always grown in mixtures and is useful for intercropping due to its low growth habit (10–15 cm). It is not good for grazed systems.

There are several other species of medics (e.g. *Medicago littoralis* Rohde ex Lois., *Medicago tornata* (L.) Mill., *Medicago rugosa* Desr., *Medicago denticulata* Willd., *Medicago minima* (L.) Bart., *Medicago laciniata* (L.) Miller and *Medicago polymorpha* L.) that could be used for LGMs in Mediterranean climates with mild winters.

Vetches

Vicia sativa L. (common vetch or tares) and *Vicia villosa* L. (hairy vetch) are long, trailing annual plants suitable for winter- spring- or summer-sown LGMs. They are protein-rich forage crops, often grown in a mixture with a cereal that provides physical support.

Trefoils

The genus *Lotus* has several species that are grown as LGMs. Their main advantage is that they grow well on soil that is too wet, cold or acid for clovers, and this goes some way to compensate for the generally lower yields of trefoils. Their long, trailing growth habit makes them well suited to mixtures, although they attain high biomass only after many months of growth.

Sweet clovers

Melilotus spp. are biennials that are drought-resistant and tolerant of poor soil conditions, although they prefer warmer climates. These large (up to 2 m tall), productive plants are tolerant of grazing and have a high protein content. Their deep, penetrating root systems can help improve soil structure.

Lupins

There are several lupin species that are grown in LGMs, such as white lupin (*Lupinus albus* L.), bitter blue or narrow-leafed lupin (*Lupinus angustifoilus* L.) and yellow lupin (*Lupinus luteus* L.). They are large annual plants that perform well on poor, light soils and are somewhat tolerant of acidic conditions. Lupins are generally grown in warmer climates and are used for grazing or silage production.

Faba bean and pea

Although most commonly grown for grain, faba bean (*Vicia faba* L.) is a high-biomass overwintering species that can be incorporated during spring or cut down and allowed to regrow before incorporation. There are many cultivars of pea (*Pisum sativum* L.) that can be used in LGMs, but spring cultivars have low tolerance to frost so winter cultivars are recommended in cooler climates. Mixtures of cereals with grain legumes allow the former to physically support the latter. A drawback is that seed costs can be high.

Non-legume companion species

Legume-only stands tend to accumulate, via fixation, high levels of N, some of which is likely to be lost during the winter by leaching. However, if they are mixed with non-legumes that risk is much reduced as the non-legume takes up N. For example, a mixture of clover and grass is as efficient in taking up N from the soil as pure stands of grass, and the green matter contains about as much N late in the autumn as a pure stand of clover (Bergkvist *et al.*, 2011). There is also a grass sink effect (see Humphreys *et al.*, Chapter 9, this volume). When N is lost from the clover during winter, it can be taken up again by the grass as soon as it reassumes growth in the spring. Winter annual legumes can, for the same reason, be mixed with a winter annual cereal crop, such as rye.

Species-rich mixtures of legumes

Most LGMs are relatively simple mixtures of a legume with another species such as a grass or brassica, as described above. While these systems perform well in the right conditions, their reliance on just a few species can be a drawback. Well-designed mixtures of many species of legumes have the potential to mitigate this issue. The legume component especially is susceptible to failure if the weather conditions prevent good establishment or growth. Conditions that are unfavourable for one legume species in the mixture may favour the growth of another. Where a simple mixture is included in a rotation, the lack of variation in chemical composition means that N release to a following arable crop may not be synchronized with the N demands of that crop. However, variations in chemical compositions between species in a complex mixture mean that they decompose at varying rates, leading to a more even supply of N to following crops. Furthermore, species-rich LGMs inherently have the flexibility to be designed, increasing biodiversity and providing a range of desired ecosystem services such as nectar provision for pollinators (Malézieux *et al.*, 2009).

In general, the greater the number of legume species in a mix, the greater the potential to provide a wide range of functions. However, in agricultural situations, there is an inevitable trade-off between these wider functions and the overriding driver of agricultural production. A recent study in the UK concluded that the optimum number of legume species in a mixture for most agricultural purposes is three (Storkey *et al*., 2015). However, if there are specific goals such as weed suppression then the number of species can be increased. The mix can also be tailored to match soil and environmental conditions. This multifunctionality is an increasingly important aspect of agricultural systems and is more readily delivered by a species-rich LGM than by the main cash crop phases of a rotation.

Crop Management

Establishment

Seeds of many legumes used as green manures are often more expensive than those of non-leguminous green manure crops, so it is important to take steps to ensure optimum conditions for germination and maximum ground cover from the resulting LGM. The first step is the preparation of a good seedbed with a fine tilth and adequate moisture levels prior to drilling or broadcasting. Drilling is a better method for many species, especially those with large seeds such as vetches that are attractive to birds. It enables good control over the depth of sowing. However, mixtures often contain species with a large range of seed sizes and this may be technically difficult to handle with a drill unless multiple passes are made. Broadcasting can address many of the above problems, although seed size range can still be a concern. After broadcast, seed may be incorporated into the soil by light harrowing or rolling.

Successful N fixation by legumes requires the presence of the appropriate strain of rhizobium and this will not always be present in the soil. This is particularly a problem where non-native legumes are grown and can be alleviated by inoculation of the seed before sowing. For example, most lucerne seed sold in the UK is pre-coated with inoculum. Alternatively, inoculum mixes that are added to seeds at sowing are widely available commercially and it is also possible for farmers to produce their own, at least on a small scale.

A further consideration is the availability of suitable seed. Many of the less common species that might be used for LGMs are not produced in large quantities and may suffer from fluctuations in availability. This is particularly true if certified seed is required for organic systems, although derogation for a proportion of a mixture to be non-organic may be possible.

Sowing time

Although the timing of sowing is critically important, it is difficult to give precise guidance as it depends on the combination of climate and species, plus the myriad local conditions that also must be taken into account. In general, most

LGMs perform well if sown in the spring and early summer and are sown after risk of frost has passed but in time to allow good establishment before summer drought restricts growth. In contrast, only a few species of legumes are suitable for autumn sowing in northern Europe. If they are sown too late, the plants may establish poorly or not be large enough to survive winter, but if they are sown too early they can reach their reproductive stage in autumn and lose winter hardiness. In practice, large-seeded species are often the best choice for late sowing as they tend to have a higher relative growth rate, and sowing at a higher seed rate can mitigate establishment issues. In addition to the direct impact of sowing time on plant establishment, consideration must also be given to the necessity to fit in with the sequence of crop rotation, which is discussed later in the chapter.

Fertilization

The amount of legume and the proportion of it in an LGM mixture can largely be determined by management, whereas the amount of any grass during the first growing season can be effectively determined by the seed rate or by the time of undersowing (Ohlander *et al.*, 1996). While these latter factors have some importance for legumes, they are not nearly as important as the amount of N fertilizer used. Many studies have reported a large decrease in the legume component of LGMs when high levels of N are applied (Ohlander *et al.*, 1996; Bergkvist *et al.*, 2011). This effect is species-specific, with, for example, red clover being more tolerant of high N levels than white clover. While many LGMs are grown without fertilizer, this effect should be borne in mind in cases such as intercropping or undersowing where some fertilizer may be applied for the benefit of the accompanying crop.

Cutting and grazing

Unless an LGM is in the ground for only a matter of months or grown as part of an intercrop, some management, in terms of cutting or grazing, will be required. This tends to make the LGM more productive overall and increase the total amount of N fixed (Hatch *et al.*, 2007; Dahlin and Stenberg, 2010). If cutting is carried out, then there is a question of what to do with the clippings. A commonly practised system is 'cut and mulch', where the clippings are left in place. This has the advantages of helping to control weeds and not removing nutrients such as phosphorus (P) and potassium (K) from the system, but N fixation may be reduced due to the process returning relatively N-rich material to the system. Care must also be taken not to let the LGM get too tall before cutting and to use a mower that will chop the clippings, otherwise the crop may be smothered by the cut material. The alternative is to remove the clippings, which may then be sold or used elsewhere for feed or compost. This increases the flexibility to the farmer but risks depletion of soil nutrients in the longer term. Not all legumes are suitable for cutting or must be cut high to avoid removal of aerial buds, making species selection important.

As with cutting, not all legumes are suitable for grazing as their growth habit makes them unable to regenerate well (e.g. crimson clover). Of those that are suitable, some (e.g. white clover and lucerne) can cause bloat in ruminants unless the grazing regime is carefully managed. Alternatively, low-bloat legumes such as birdsfoot trefoil and sainfoin may be grown. Whatever species are sown originally, the species composition will change over time more rapidly in grazed swards than in those that are cut, due to the selectivity of grazers. These problems are usually worth some effort to overcome, as grazed LGMs are capable of delivering greater yields of high-quality, protein-rich forage than grass-only systems, and with a reduced N requirement both during growth and for the following crop (Martens and Entz, 2011).

Incorporation

The method and timing of incorporation of an LGM into the soil are some of the most important processes governing N availability to the following crop. The choice of method is dictated to a certain extent by the choice of species grown and prior management. In anything other than well-grazed swards, the first stage will probably be a reduction in the bulk of the LBM through cutting with a mower or harrow. After the material has dried sufficiently, further incorporation can then take place. Ploughing is a good and commonly used method that is effective. It does not mix plant and soil particularly well, and if done too deeply may retard N release. Harrowing can mix the plant and soil effectively but does not do so to any great depth in the soil. Rotary tillage offers a combination of these processes, but comes at the expense of high power requirements.

In practice, the timing of incorporation is often chosen to fit with farm operations and the agronomic requirements of cash crops in the rotation. Whether spring or autumn, it is important that incorporation happens so that the release of N is synchronized with crop requirements, to avoid the loss of excess N from the system (Cook *et al.*, 2010; Dabney *et al.*, 2010; Campiglia *et al.*, 2011). N losses in the form of N leaching and nitrous oxide (N_2O) emissions dominate, depending on timing of soil incorporation and climatic conditions (Ball *et al.*, 2007; Olesen *et al.*, 2009; Askegaard *et al.*, 2011) and ammonia volatilization may be a particular issue in Mediterranean climates (Rana and Mastrorilli, 1998). These N losses reduce the possible N supply to following crops, and also constitute environmental burdens with N leaching contributing to eutrophication of aquatic ecosystems and N_2O being a potent greenhouse gas.

Effects of Legume Green Manures

Supply of N to following crops

The main agronomic reason for growing LGMs is to add N to the system that can be used by a following cash crop. N accumulated by the LGM is released into the soil after incorporation through the process of mineralization by soil microbes

(Murphy *et al.*, 2004). The rate at which this complex process occurs is governed by many factors such as temperature, moisture availability and the chemical composition (quality) of the LGM residue (Cadisch *et al.*, 1998). Key to this is the ratio of carbon (C) to N, and the form of that C because structural components such as lignin are more resistant to decomposition. As these parameters vary with species, the quality of the LGM residue can be manipulated by the selection of appropriate species. Thus plants with large, N-rich leaves such as red clover will break down more rapidly than woodier species such as mature lucerne, and all legumes decompose faster than grasses.

The amount of N realized by European LGMs depends on a diverse range of factors, and many studies have attempted to quantify it (e.g. Mueller and Thorup-Kristensen, 2001; Cuttle *et al.*, 2003). Overall the results are highly variable, with figures ranging from almost zero to over 500 kg/ha of N. In practice, most LGMs may correspond to fertilizer N applications of up to 100–200 kg/ha. Higher figures tend to be associated with highly managed, shorter-term LGMs whereas more extensive, less managed systems may deliver 50 kg/ha of N or less.

Effects on other soil properties

In addition to the effects on N, the incorporation of LGMs may improve many different indicators of soil quality such as aggregate stability, labile organic matter and soil faunal activity (Biederbeck *et al.*, 1998; Birkhofer *et al.*, 2011), Some of these changes, especially in soil organic matter, may only be evident in the long term (Stobart and Morris, 2011; O'Dea *et al.*, 2013).

The growth and incorporation of an LGM can enhance biological P cycling in soil and improve the dissolution and bioavailability of soluble phosphate rock (Barea *et al.*, 2002). Changes in the soil pH following the growth of an LGM can also increase availability of P and K, while reducing losses due to runoff and leaching (e.g. Scott and Condron, 2003). In grass/clover leys, there is high absorption of K, probably due to the combination of shallower and deeper roots of the two crop species.

Rotational Considerations

As there is often no direct economic gain from the growth of LGMs, it is important that they are as productive as possible and compatible with the main cash crops that will be grown. The cash crops grown may place restrictions on which legume species are grown, and set the schedule for their planting and incorporation. It is vital that a proper assessment is made of the likely N input from the LGM, so that the amount of any supplementary N can be calculated accurately. Finally, an economic assessment reveals the financial implications of the choices made.

In northern Europe, white and red clover, the most frequently used legume species in LGMs, are often undersown in spring into crops of spring cereals. If they are sown in autumn in areas with cold and long winters, such as in Scandinavia, their sowing time needs to be early enough so they can survive the winter (Laidlaw and McBride, 1992; Brandsæter *et al.*, 2002). Winter crops, such as wheat and rye, yield highest after sowing in September and undersown legumes would generally not survive winter if sown much later. Further south, in Germany and the southern UK, clover species can be sown with winter cereals in autumn and still survive winter (e.g. Heyland and Merkelbach, 1991).

Legumes alone or mixed with cereals or brassicas are the most common species cultivated in southern areas of Europe as LGMs. In addition to the typical species grown for forage or grain (e.g. faba bean, vetch or clover) other legumes such as narbon vetch (*Vicia narbonensis* L.) or lupins may be used. In areas with hot, dry summers, where water competition with the main crop is possible, LGMs are avoided during the summer and limited to cover the soil in olive groves or vineyards during the winter season.

After the harvest of the main crop, an undersown LGM is left to grow during autumn and can be incorporated before winter, in early spring before sowing of a spring crop or in the summer before sowing of an autumn-sown crop. It is generally only organic farmers that let the LGM grow for a whole summer to control weeds by repeated mowing and to add N to the system. In northern Europe, however, it has recently become less common for LGMs to be grown only for fixing N and to control weeds. Generally, farmers who have no use of the LGM as fodder will sell the green biomass, although this will reduce the beneficial effects to the following crop.

Winter annual legumes (e.g. vetch) may be sown after harvest of one crop in July or in the beginning of August. The following spring they are incorporated or grown on to become living or dead mulch for a spring crop, to provide it with N and to control small-seeded weeds. The major part of the growth and N fixation will occur during spring, so autumn incorporation is not the best option. An important feature of autumn-sown LGMs is that they are unlikely to fix significant quantities of N unless they are allowed to grow through the following summer, which is likely only in organic systems. If a green manure is required purely for the overwinter period, then one without legumes may be a more flexible option.

N budgets

Given that one of the main reasons that LGMs are grown is the input of N they provide to the system, it is vital that this input is taken into account when considering what further additions of N may be required for a following crop. This is problematic, as it is the result of interactions between many complex processes that control both the amount of N fixed and the amount transferred to a following crop, as detailed above. While the effects of changes in any one parameter in isolation are generally well known and predictable, forecasting in a field-based system with many uncontrolled variables is challenging. One approach is the use of computer-based models and many of these are now available. Some are aimed at the scientific user and require detailed knowledge of many variables. Others are designed to be used by farmers and advisors, such as the FBC model (Cuttle, 2006) and later versions of NDICEA (van der Burgt *et al.*, 2006), which require relatively simple inputs that farmers are likely to know or can easily assess, to produce guidance as to the amount of N available from LGMs.

Economics

The economic impact of growing LGMs is highly dependent on the design of the system. Whether the LGM is grown as a main crop, as an undersown crop or as an intercrop, the gross margin of the whole crop rotation has to be considered because of the positive internal effects of legumes (listed below). This is due to the simple sum of the individual gross margins of the cash crops with the variable costs of the LGM crops (Weitbrecht and Pahl, 2000).

An important effect of an LGM is the potential reduction of the use of synthetic N fertilizer. One way to assess the economic benefits is therefore to compare the costs of N fixed from the LGM and the costs of N of mineral fertilizers. The price of N gained by LGMs can be calculated from their N profit and their variable costs. The variable costs of an LGM depend mainly on the seed costs, establishment and management costs. Since these costs are relatively high, the resulting price of the N is higher than that from synthetic fertilizer (Knight *et al.*, 2010).

To consider all internal effects it is recommended that the total gross margin of the whole crop rotation is considered. If an LGM replaces a main cash crop, the financial loss of not growing this crop has to be included in the calculation as foregone revenue, together with the variable costs of the LGM (seed, establishment and management). These are the total costs to be considered for the integration of the LGM.

An LGM significantly increases the yield of the subsequent crop (Knight *et al.*, 2010). The resulting gain in value of the following crop must be considered, but is highly dependent on the market price. In addition, the savings made in N fertilizers, pesticides and soil cultivation to the following crop have to be taken into account in the calculation.

In conclusion, the economic benefits of LGMs depend mainly on the costs of the LGM, on the value of the replaced crop and any gains in the subsequent crop. The ratio of these costs and gains determines whether growing an LGM results in a financial benefit. It is also important to remember that LGMs may have many additional effects such as the supply of additional on-farm fodder, which can be included in an economic analysis, or an impact on soil erosion which is difficult to quantify economically.

Conclusion

LGMs are widely used across Europe in a diverse range of cropping systems. Significant regional variations mean that they are optimized for local growing conditions and patterns of crop rotations. LGMs are key to successful organic systems, in which a significant part of the crop rotation is often devoted to their growth. Due to rising costs of synthetic inputs and concerns over the environmental performance of agriculture, there is increased interest in expanding the use of LGMs in non-organic systems. Although the traditional focus has been on the supply of N, they have a wide range of potential benefits that include improving soil quality, reducing soil erosion and increasing the biodiversity of farmland. However, LGMs will not be agronomically or economically viable in all systems and in these cases other types of green manures may be more appropriate. As demand for multi-functional agricultural systems grows, and is increasingly required by European agricultural policies, so does the potential for greater use of LGMs.

References

Askegaard, M., Olesen, J.E., Rasmussen, I.A. and Kristensen, K. (2011) Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management. *Agriculture Ecosystems and Environment* 142, 149–160.

Ball, B.C., Watson, C.A. and Crichton, I. (2007) Nitrous oxide emissions, cereal growth, N recovery and soil nitrogen status after ploughing organically managed grass/clover swards. *Soil Use and Management* 23, 145–155.

Barea, J.M., Toro, M., Orozco, M.O., Campos, E. and Azcon, R. (2002) The application of isotopic ((32)P and (15)N) dilution techniques to evaluate the interactive effect of phosphate-solubilizing rhizobacteria, mycorrhizal fungi and *Rhizobium* to improve the agronomic efficiency of rock phosphate for legume crops. *Nutrient Cycling in Agroecosystems* 63, 35–42.

Bergkvist, G., Stenberg, M., Wetterlind, J., Bath, B. and Elfstrand, S. (2011) Clover cover crops under-sown in winter wheat increase yield of subsequent spring barley – effect of N dose and companion grass. *Field Crops Research* 120, 292–298.

Biederbeck, V.O., Campbell, C.A., Rasiah, V., Zentner, R.P. and Wen, G. (1998) Soil quality attributes as influenced by annual legumes used as green manure. *Soil Biology and Biochemistry* 30, 1177–1185.

Birkhofer, K., Diekötter, T., Boch, S., Fischer, M., Müller, J., Socher, S. and Wolters, V. (2011) Soil fauna feeding activity in temperate grassland soils increases with legume and grass species richness. *Soil Biology and Biochemistry* 43, 2200–2207.

Brandsæter, L.O., Olsmo, A., Tronsmo, A.M. and Fykse, H. (2002) Freezing resistance of winter annual and biennial legumes at different development stages. *Crop Science* 42, 437–443.

Cadisch, G., Handayanto, E., Malama, C., Seyni, F. and Giller, K.E. (1998) N recovery from legume prunings and priming effects are governed by the residue quality. *Plant and Soil* 205, 125–134.

Campiglia, E., Mancinelli, R., Radicetti, E. and Marinari, S. (2011) Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper crop (*Capsicum annuum* L.). *Nutrient Cycling in Agroecosystems* 39, 399–412.

Cook, J.C., Gallagher, R.S., Kaye, J.P., Lynch, J. and Bradley, B. (2010) Optimizing vetch nitrogen production and corn nitrogen accumulation under no-till management. *Agronomy Journal* 102, 1491–1499.

Cuttle, S.P. (2006) Development of the FBC model to estimate the nitrogen available from fertility-building crops in organic rotations. *Aspects of Applied Biology* 79, 259–262.

Cuttle, S., Shepherd, M. and Goodlass, G. (2003) A review of leguminous fertility-building crops, with particular reference to nitrogen fixation and utilisation. Department for Environment, Food and Rural Affairs (Defra) Project Report OF0316: The development of improved guidance on the use of fertility-building crops in organic farming Defra, London.

Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H. and Liebig, M.A. (2010) Using cover crops and cropping systems for nitrogen management. In: Delgado, J.A. and Follett, R.F. (eds) *Advances in Nitrogen Management for Water Quality*. Soil and Water Conservation Society, Ankeny, Iowa, pp. 231–282.

Dahlin, A. and Stenberg, M. (2010) Transfer of N from red clover to perennial ryegrass in mixed stands under different cutting strategies. *European Journal of Agronomy* 33, 149–156.
Hatch, D.J., Goodlass, G., Joynes, A. and Shepherd, M.A. (2007) The effect of cutting, mulching and applications of farmyard manure on nitrogen fixation in a red clover/grass sward. *Bioresource Technology* 98, 3243–3248.
Heyland, K.U. and Merkelbach, H. (1991) Die Möglichkeiten des Einsatzes von Untersaaten zur Unkrautunterdrückung sowie Konkurrenzwirkungen von Unkraut und Untersaat auf die Ertragsbildung des Winterweizens. *Bodenkultur* 42, 347–359.
Knight, P., Lacey, T., Heading, E., Will, T., Rayns, F. and Rosenfeld, A. (2010) Extension of FV 299 – investigation into the adoption of green manures in both organic and conventional rotations to aid nitrogen management and soil structure. Final report of Horticultural Development Council project FV299a. Available at: http://horticulture.ahdb.org.uk/sites/default/files/research_papers/FV 299a Final report 2010.pdf (accessed 18 October 2016).
Laidlaw, L.S. and McBride, J. (1992) The effect of time of sowing and sowing method on production of white clover in mixed swards. *Grass and Forage Science* 47, 203–210.
Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., de Tourdonnet, S. and Valantin-Morison, M. (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development* 29, 43–62.
Martens, J.R.T. and Entz, M.H. (2011) Integrating green manure and grazing systems: a review. *Canadian Journal of Plant Science* 91, 811–824.
Mueller, T. and Thorup-Kristensen, K. (2001) N-fixation of selected green manure plants in an organic crop rotation. *Biological Agriculture and Horticulture* 18, 345–363.
Murphy, D.V., Stockdale, E.A., Hoyle, F.C., Smith, J.U., Fillery, I.R.P., Milton, N., Cookson, W.R., Brussaard, L. and Jones, D.L. (2004) Matching supply with demand. In: Hatch, D.J., Chadwick, D.R., Jarvis, S.C. and Roker, J.A. (eds) *Controlling Nitrogen Flows and Losses, Proceedings of the 12th International Nitrogen Workshop*, Exeter, UK, 21–24 September 2003, pp 101–112.
O'Dea, J.K., Miller, P.R. and Jones, C.A. (2013) Greening summer fallow with legume green manures: on-farm assessment in north-central Montana. *Journal of Soil and Water Conservation* 68, 270–282.
Ohlander, L., Bergkvist, G., Stendahl, F. and Kvist, M. (1996) Yield of catch crops and spring barley as affected by time of undersowing. *Acta Agriculturae Scandinavica Section B – Soil and Plant Science* 46, 161–168.
Olesen, J.E., Askegaard, M. and Rasmussen, I.A. (2009) Winter cereal yields as affected by animal manure and green manure in organic arable farming. *European Journal of Agronomy* 30, 119–128.
Pieters, A.J. (1927) *Green Manuring Principles and Practice*. Wiley, New York.
Rana, G. and Mastrorilli, M. (1998) Ammonia emissions from fields treated with green manure in a Mediterranean climate. *Agricultural and Forest Meteorology* 90, 265–274.
Scott, J.T. and Condron, L.M. (2003) Dynamics and availability of phosphorus in the rhizosphere of a temperate silvopastoral system. *Biology and Fertility of Soils* 39, 65–73.
Stobart, R.M. and Morris, N.L. (2011) New Farming Systems Research (NFS) project: long term research seeking to improve the sustainability and resilience of conventional farming systems. *Aspects of Applied Biology* 113, 15–23.
Storkey, J., Döring, T., Baddeley, J., Collins, R., Roderick, S., Jones, H. and Watson, C. (2015) Engineering a plant community to deliver multiple ecosystem services. *Ecological Applications* 25, 1034–1043.
van der Burgt, G.J.H.M., Oomen, G.J.M., Habets, A.S.J. and Rossing, W.A.H. (2006) The NDICEA model, a tool to improve nitrogen use efficiency in cropping systems. *Nutrient Cycling in Agroecosystems* 74, 275–294.
Weitbrecht, B. and Pahl, H. (2000) Lohnt sich der Anbau von Körnerleguminosen? [Is growing pulse crops economical?] *Ökologie and Landbau* 116, 39–41.